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THESIS

PARAMETRIC STUDY OF THE DYNAMIC STABILITY OF TOWED SHIPS

by

David L. Kolthoff

June, 1989

Thesis Advisor: Prof. F. A. Papoulias

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Several accidents in towing operations of barges or disabled ships in restricted waters have made necessary the investigation of the course keeping stability of towed vessels. In this work a non-linear model is used to simulate the slow surge, sway, and yaw motions of a vessel towed by a heavy catenary towline. The effect of geometric parameters of the system on the stability of equilibrium configurations is analyzed. It is shown that for certain choices of towing system parameters, dynamic loss of stability may occur which results in qualitatively different asymptotic response. The results of this study identify regions in the parameter space that lead to either safe operations or hazardous system response.

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Parametric Study of the Stability of Towed Ships

by

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Lieutenant Commander, United States Navy
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Submitted in partial fulfillment of the
requirements for the degree of

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PARAMETRIC STUDY OF THE DYNAMIC STABILITY OF TOWED VESSELS

Several accidents in towing operations of barges or disabled ships in restricted and open waters have made necessary the investigation of the course keeping stability of towed vessels. In this work a non-linear mathematical model is used to simulate the slow surge, sway, and yaw motions of a vessel towed by a heavy catenary towline. The effect of geometric parameters of the system on the stability of equilibrium configurations is analyzed.

It is shown that for certain choices of towing system parameters, dynamic loss of stability may occur which results in qualitatively different asymptotic response. The results of this study identify regions in the parameter space that lead to either safe operations or hazardous system response.

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I. INTRODUCTION

A. BACKGROUND

A long history of towing accidents resulting in loss of life, damage to property, and pollution of the environment have prompted many studies into the dynamics of towing operations. Of primary concern was the motions of the towed vessel in the horizontal plane (yaw, sway, and surge). Excessive and unstable motions could lead to collisions and capsizing. The ability to predict the motion of a particular towing system would be of particular benefit to ship designers and towing operators, by identifying those situations where the towing operations would be the safest, or those which must be avoided.

Previous studies at the University of Michigan and elsewhere had developed mathematical models and numerical techniques to analyze towing dynamics, and had identified those parameters which are of primary importance to the stability of the towing system. The linear model usually used to describe ship motions [Ref. 1, Chapter 7] is inadequate for the towing problem. Non-linear models, as in [Ref. 2], must be utilized to accurately describe the towing system. These studies had identified the position of

the towline attachment point on the towed vessel and the towline tension as the most significant (and controllable) parameters of the towing system.

B. PROBLEM CONDITIONS

In this study, computer programs developed in [Ref. 3] were used to analyze the effect of different parameter combinations on the towed stability of three vessels. These programs use bifurcation to identify the unstable and stable regions of the parameter space. The principal parameters studied were (Fig.1):

1. longitudinal position of the towline attachment point forward of the towed vessel's center of gravity, xp;
2. athwartships position of the towline attachment point port or starboard of the towed vessel's centerline, yp;
3. length of the towline, Lw.

In the model used in this study, unlike [Ref. 2], the towline is modeled as an inextensible caternary, thus making towline tension a function of its length. The model conditions were:

1. speed of towing vessel of 2 knots;
2. towing vessel on steady course;
3. calm seas, no wind; i.e., no external environmental forces.

Characteristics of the towed vessel were inputted into the programs from a data file containing hydrodynamic coefficients, resistance data, towline characteristics, and

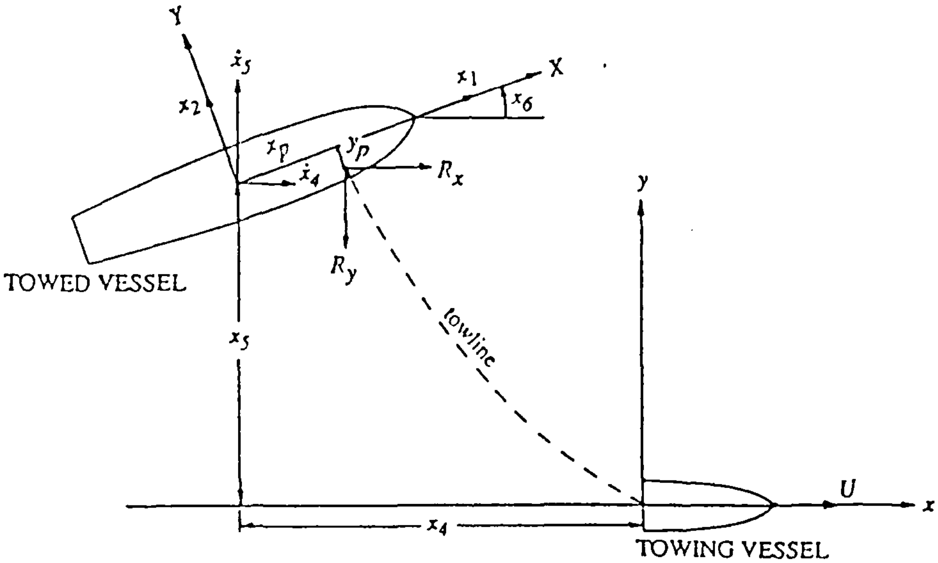


Figure 1. Problem Geometry

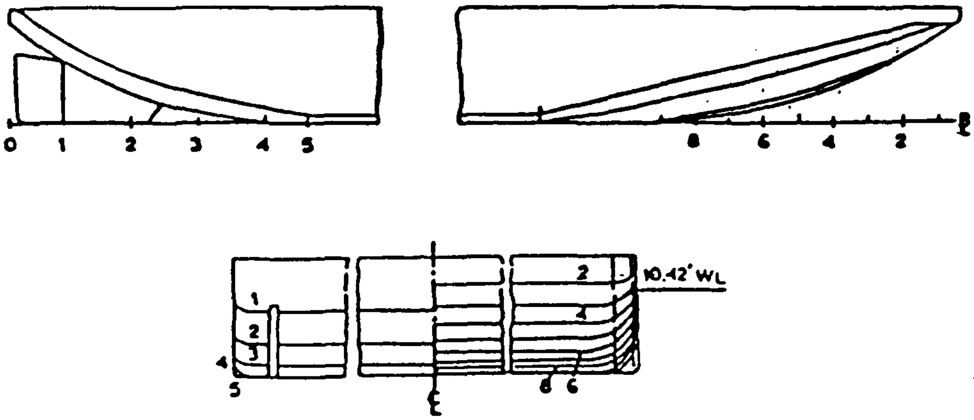
skeg data, if applicable. The effect of asymmetrical forces acting on the towed vessel, such as the presence of a propellor or an environmental force, are introduced through a bias in the data file. All dimensions are nondimensionalized with respect to the towed ship's length between perpendiculars (LBP).

Three vessels were studied (Fig.2):

1. a 191 foot barge with a skeg, with no propellor (i.e., no bias);
2. a 1066 foot tanker with no skeg, but with a propellor (i.e., with a bias);
3. the same barge as in 1), but without the skeg and with a propellor (i.e., with a bias).

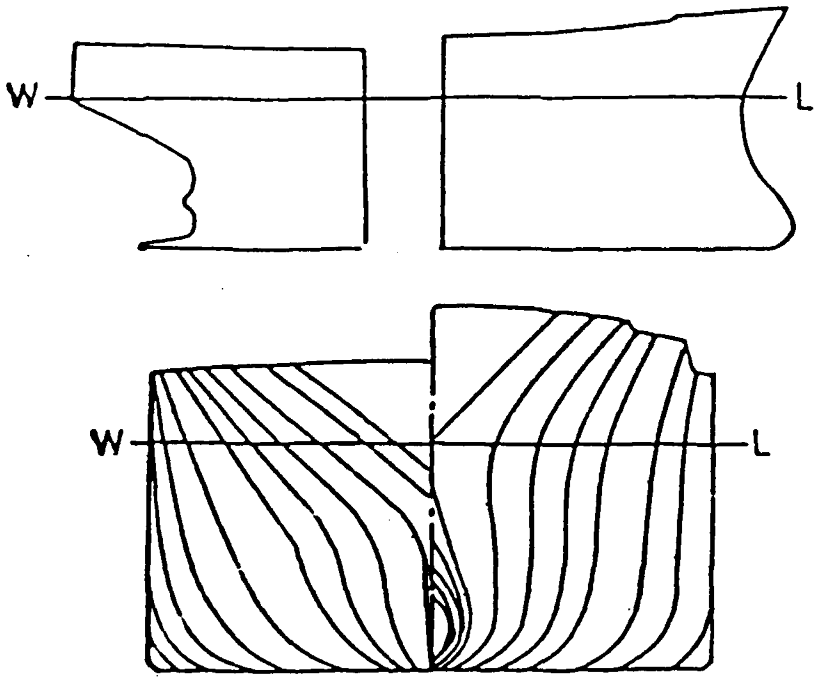
Unlike previous studies, this work includes the effect of athwartship position of the towline attachment point in the stability of the towing system.

Chapter II provides background into the problem formulation and stability analysis used in this study. Chapter III presents the results of the analysis and discusses some practical aspects of these results. Chapter IV discusses the conclusions which can be made from the results of this study on the stability of the towing system and the use of the techniques used herein.



* Barge with skeg, no bias

* Barge with no skeg, with bias



* Tanker with bias

Figure 2. Body Plans of Vessels Studied

II. PROBLEM FORMULATION AND METHOD OF APPROACH

Slow motions of a towed vessel in the horizontal plane are described by a system of six nonlinear, coupled, differential equations. [Ref. 4 and 5] In its standard form this system is

$$\dot{x}_1 = \frac{1}{m - X_{\dot{u}}}[F_1(x_1,x_2,x_3) + T_{surge}(x_4,x_5,x_6)]$$

$$\dot{x}_2 = \frac{I_z - N_{\dot{r}}}{D}[F_2(x_1,x_2,x_3) + T_{sway}(x_4,x_5,x_6)]$$

$$+ \frac{Y_{\dot{r}}}{D}[F_3(x_1,x_2,x_3) + x_pT_{sway}(x_4,x_5,x_6)-y_pT_{surge}(x_4,x_5,x_6)],$$

$$\dot{x}_3 = \frac{N_{\dot{v}}}{D}[F_2(x_1,x_2,x_3) + x_pT_{sway}(x_4,x_5,x_6)]$$

$$+ \frac{m - Y_{\dot{v}}}{D}[F_3(x_1,x_2,x_3)+x_pT_{sway}(x_4,x_5,x_6)-y_pT_{surge}(x_4,x_5,x_6)],$$

$$\dot{x}_4 = x_1\cos x_6 - x_2\sin x_6 - U,$$

$$\dot{x}_5 = x_1\sin x_6 + x_2\cos x_6,$$

$$\dot{x}_6 = x_3,$$

where

$$T_{surge}(x_4,x_5,x_6) = R_x(x_4,x_5,x_6)\cos x_6+R_y(x_4,x_5,x_6)\sin x_6,$$

$$-T_{sway}(x_4,x_5,x_6) = R_x(x_4,x_5,x_6)\sin x_6-R_y(x_4,x_5,x_6)\cos x_6,$$

D denotes the known quantity

$$D = (m-Y_v)(I_z-N_r)-Y_rN_v,$$

and

$$F_1(x_1,x_2,x_3)=X_ux_1+\tfrac{1}{2}X_{uu}x_1^2+1/6X_{uuu}x_1^3+\tfrac{1}{2}X_{vv}x_2^2+\tfrac{1}{2}X_{vvu}x_2^2x_1$$
$$+\tfrac{1}{2}X_{rr}x_3^2+\tfrac{1}{2}X_{rru}x_3^2x_1+(X_{vr}+m)x_2x_3+X_{rvu}x_1x_2x_3,$$

$$F_2(x_1,x_2,x_3)=Y_0+Y_{0u}x_1+Y_{ouu}x_1^2+Y_vx_2+1/6Y_{vvv}x_2^3+\tfrac{1}{2}Y_{vrr}x_2x_3^2$$
$$+Y_{vu}x_1x_2+\tfrac{1}{2}Y_{vuu}x_2x_1^2+(Y_r-mx_1)x_3+1/6Y_{rrr}x_3^3+\tfrac{1}{2}Y_{rvv}x_3x_2^2$$
$$+Y_{ru}x_3x_1+\tfrac{1}{2}Y_{ruu}x_3x_1^2,$$

$$F_3(x_1,x_2,x_3)=N_0+N_{0u}x_1+N_{ouu}x_1^2+N_vx_2+1/6N_{vvv}x_2^3+\tfrac{1}{2}N_{vrr}x_2x_3^2$$
$$+N_{vu}x_1x_2+\tfrac{1}{2}N_{vuu}x_2x_1^2+N_rx_3+1/6N_{rrr}x_3^3+\tfrac{1}{2}N_{rvv}x_3x_2^2$$
$$+N_{ru}x_3x_1+\tfrac{1}{2}N_{ruu}x_3x_1^2.$$

In the above equations, x_1 denotes the sway velocity in surge (longitudinal motion) of the towed vessel, x_2 the velocity in sway (lateral motion), x_3 the angular velocity in yaw (turning motion about the vertical axis), x_4 and x_5 the coordinates of the center of gravity of the towed vessel

with respect to an (x,y)-coordinate system moving with the towing vessel, and x_6 the towed vessel yaw angle. Further, U is the steady towing vessel velocity in the x-direction, xp and yp are the coordinates of the towline connection point on the towed vessel with respect to an (X,Y)-coordinate system with its origin at the towed vessel center of gravity, and R_x, R_y are the towline restoring forces. The towing system configuration and notation conventions are shown in Figure 1. Expressions for F_1, F_2, F_3 are derived by Taylor expansion in terms of the relative velocities x_1, x_2, x_3 of the towed vessel with respect to the water. In nonlinear analysis terms up to third order are used whereas terms beyond third order and second- and higher-order acceleration terms are usually neglected. Subscripts u, v, r indicate derivative of force-moment component with respect to x_1, x_2, x_3 respectively, and subscript c indicates propellor dependent terms., which represent a source of system asymmetry. These terms are zero in the absence of a propellor. Terms X_{abc}, Y_{abc}, N_{abc}, where a, b, c are dummy independent variables representing u, v, r, are usually called slow motion derivatives. In unsteady reference motion, slow-motion derivatives are considered as functions of the frequency of motion. In our study of slowly varying reference motions, we assume that slow motion derivatives are time independent. This is a good approximation for ships with usual hull shapes and moderate speeds.

R_x and R_y denote restoring forces from the towline, and for a quasistatic towline response they are expressed as implicit functions of x_4, x_5, x_6. In this study, the model used for the towline is that of an inextensible heavy caternary with nonlinear force-displacement characteristics as given in [Ref. 3].

In compact notation the above system of six ordinary differential equations is denoted as

$$\dot{x}=f(x) \tag{1}$$

where x and f are six dimensional vectors. To analyze the stability properties of (1), the first step is to identify the equilibrium configuration of the system. For this we have to solve a system of six nonlinear, coupled algebraic equations

$$f(\bar{x})=0 \tag{2}$$

where $\bar{x}$ denotes an equilibrium configuration. It can be shown [Ref. 5] that system (2) has at most three solutions in $\bar{x}$ corresponding to three distinct equilibrium positions. In this study we concentrated our efforts on one of these equilibrium positions, namely the one which, in the absence of a bias in the system, corresponds to the towed vessel being located directly astern of the tow-tug. This is the most interesting in applications. Having computed $\bar{x}$, its stability properties can be established as follows:

Linearization of (1) around x leads to the linear system

$$\dot{z}=Az \tag{3}$$

where z represents the excursion from the equilibrium $\bar{x}$, and A is a constant 6x6 matrix. If all eigenvalues of A have negative real parts, then $\bar{x}$ is stable; otherwise it is unstable.

In this study, we performed parametric analysis of the central equilibrium in therm of towline length Lw, and the towing point coordinates with respect to the center of gravity of the towed vessel, xp and yp. These parameters can be easily changed before or during towing operations and can provide a means of passive control of the towing system. Parameter Lw directly affects the amount of tension developed by the towine. Parameter xp is directly related to the towline restoring force and moment. A small value for xp may not be able to provide adequate restoring moment and may not guarentee system stability. On the other hand a very large value for xp may result in over-compensation and therefore instability. Nonzero yp values result in a source of asymmetry introduced in the system. For a biased system (for example due to the presence of a propellor or environmental forces), it should be expected that an extra appropriate bias introduced via a nonzero yp helps counteract the effect of the former bias, and hence improve stability.

The particular equilibrium position will lose its stability when an eigenvalue of the A matrix in (3) changes its sign from negative real part to positive real part. The case when a real eigenvalue crosses zero has ben analyzed in detail in [Ref. 5]. This corresponds to a static loss of stability with generation of additional equilibrium positions in the form of solution branching. In this study we focussed our attention on the case when a complex conjugate pair crosses the imaginary axis. This corresponds to a Hopf bifurcation: the particular equilibrium experiences a dynamic loss of stability and the system begins to oscillate. The resulting periodic solutions can be stable or unstable, but at any rate, such a situation is hazardous and should be avoided during towing operations.

III. RESULTS AND DISCUSSION

A. BARGE WITH SKEG

The first vessel to be studied was an unpowered barge with a skeg aft. Since there is no propellor to introduce a bias, the barge has athwartship symmetry.

1. Figure 3: Critical Real Part vs. xp

Program TOWBIF1 calculates eigenvalues for specific Lw and yp, creates a file for each of six real and six imaginary parts, and creates a separate file containing the largest real part. The real part with the largest value is the critical indicator of the system's stability: if it is greater than zero, the system will be unstable; if less than zero, the system will be stable.

Figure 3 shows plots for the critical parts for yp=0.05 and three values for Lw. The region where the plot is greater than zero indicate that range of xp where the system is unstable. For example, for Lw=0.5 the critical real part is greater than zero for the range of xp=0.18 to xp=0.48, so the system is unstable within this range.

Note that as Lw increases, the unstable range becomes smaller, until for Lw=3.0 there is no region greater than zero. Therefore, the system will be stable for <u>all</u> values of xp; i.e, the barge should exhibit <u>no</u> unstable motion.

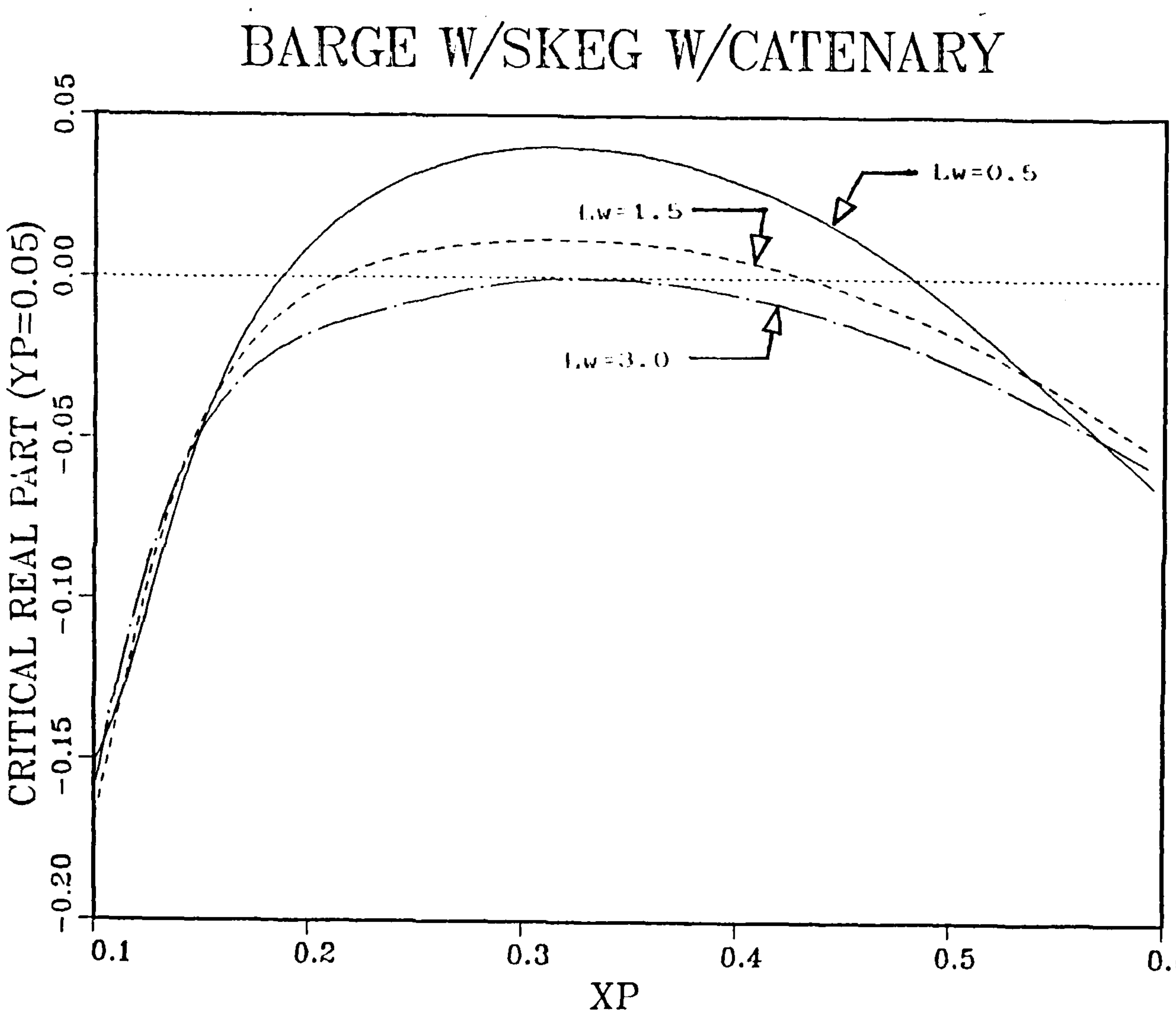


Figure 3. Critical Real Part vs. xp - Barge with skeg

2. Figure 4: yp vs. xp, Lw as Parameter

Program TOWBIF2 does the same calculations as TOWBIF1 over a range of values of yp with a given Lw, instead of a single value of yp and Lw. In essence, Figure 3 represents a cut of Figure 4 at a single value of yp and Lw. Unlike TOWBIF1, TOWBIF2 writes a point only where the critical real part changes sign. When plotted, these produce a curve delineating stable and unstable regions of the parameter space. This is the point of the process; we are more interested in finding what parameters produce stable or unstable system than the actual results of the equations of motion.

Recalling Figure 3, The area <u>inside</u> the curves represent the unstable region. For example, for Lw=0.5, the system is unstable for all values of yp within the range xp=0.2 to xp=0.5. Increasing Lw first decreases the unstable range of xp for high yp, then decreases the unstable range of yp. For large Lw (>4.0), the unstable range virtually disappears.

3. Figure 5: Lw vs. xp, yp as parameter

Program TOWBIF3 performs the same calculations as TOWBIF2, but with Lw as the ordinate and yp as the parameter. Thus Figure 5 provides the same information as Figure 4 but with a different perspective.

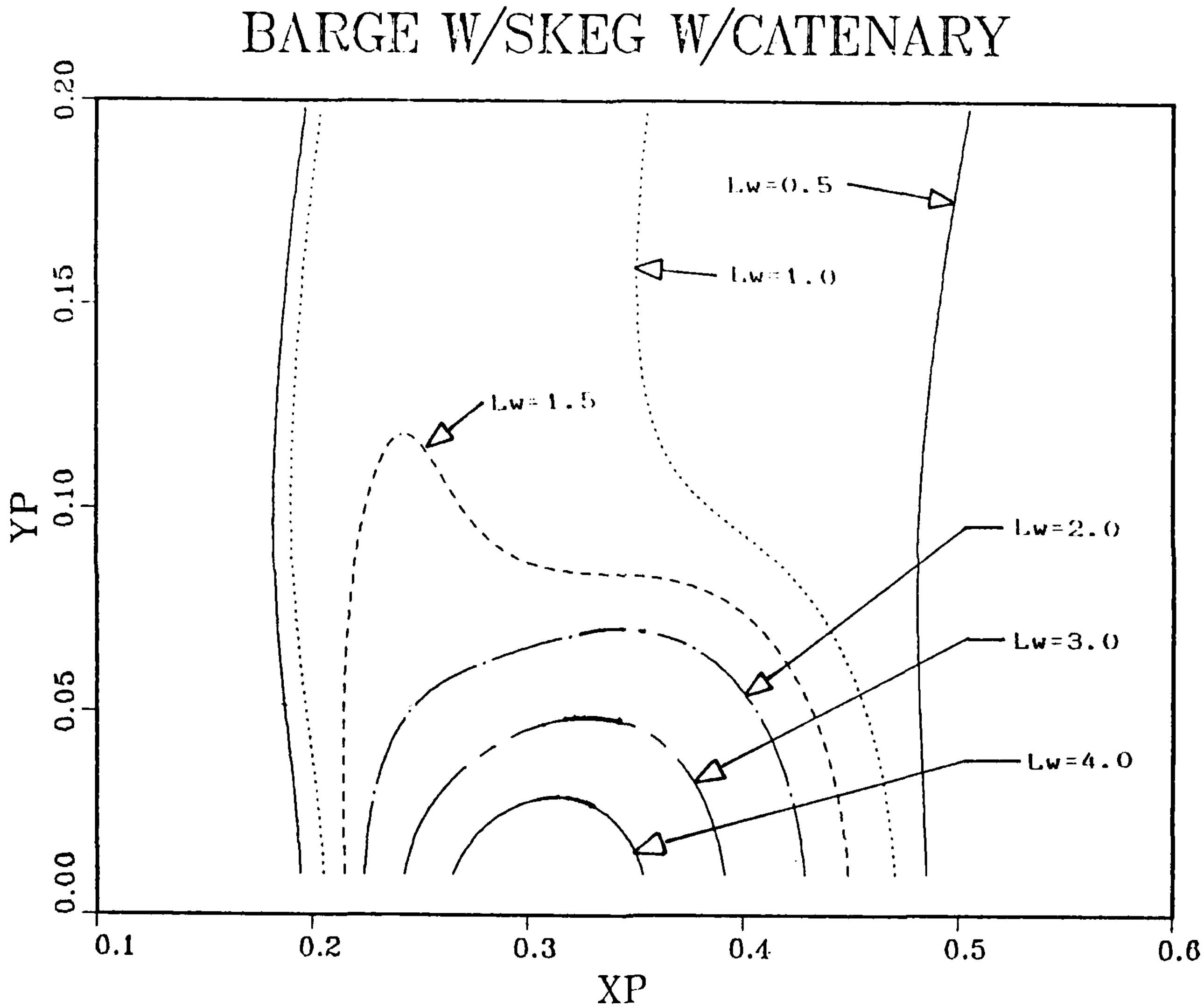


Figure 4. yp vs. xp, Lw as parameter

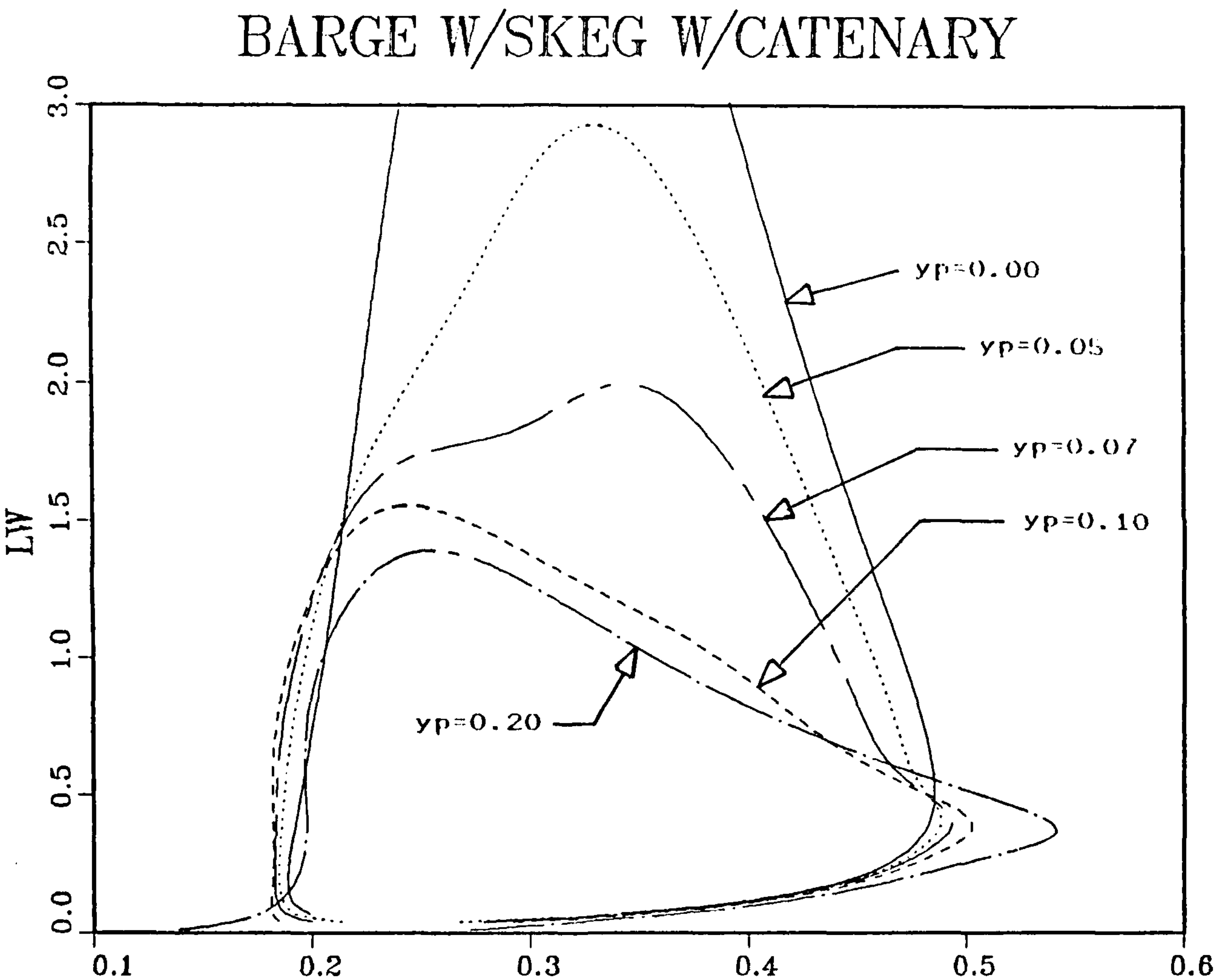


Figure 5. Lw vs. xp, yp as parameter

As in Figure 4, the unstable region is <u>inside</u> the curves. It clearly shows how increasing Lw decreases the unstable range for a constant yp, as was evident in Figure 4. It also shows that, for constant Lw greater than about 0.7, increasing yp also decreases the unstable region. In the narrow range of Lw from 0.2 to 0.7, increasing yp increases the extent of the unstable range of xp. This effect is apparent in Figure 4, but more dramatically presented in Figure 5. It would appear that using two views of the data would emphasize aspects of the curve that may be overlooked with one view.

Since positive values of yp represent port side placement of the towline attachment point, and negative values starboard side placement, both positive and negative values for yp were studied. As expected from the port-starboard symmetry of the barge, curves for positive and negative values of yp were identical, and only positive values were presented here.

From an operational point of view, one may conclude from these curves that for the unpowered barge, placing the towline on an attachment point to either side, as far forward as possible, will make the tow stable for the greatest range of towline length, but the towline should be kept no shorter than the length of the barge.

B. TANKER

The second vessel studied was a tanker typical of those now in service. The effect of the tanker's propellor makes the hull asymmetrical; this effect is represented by a bias included in the tanker data file.

1. Figure 6: Critical Real part vs xp

Figure 6 plots data generated from TOWBIF1 with yp=0.10 and two values for Lw. These plots show the stable region to be between the two zero values for the curve. Note that the stable region becomes smaller with increasing Lw.

Note also that both curves are discontinuous in their slopes. The critical real parts file is a composite of several results files, each of which is critical over a certain range. Each results file forms a smooth curve; thus the curves plotted on each TOWBIF1 figure may be combinations of the critical section of several results files.

Finally, note that the stable region occurs over a narrow range of xp, unlike the barge with skeg discussed earlier.

2. Figure 7: Lw vs. xp, yp as Parameter

Figure 7 was produced from data generated by TOWBIF3 for positive values of yp. As was shown in Figure 6, the stable region is <u>inside</u> the curves. The vertical line at

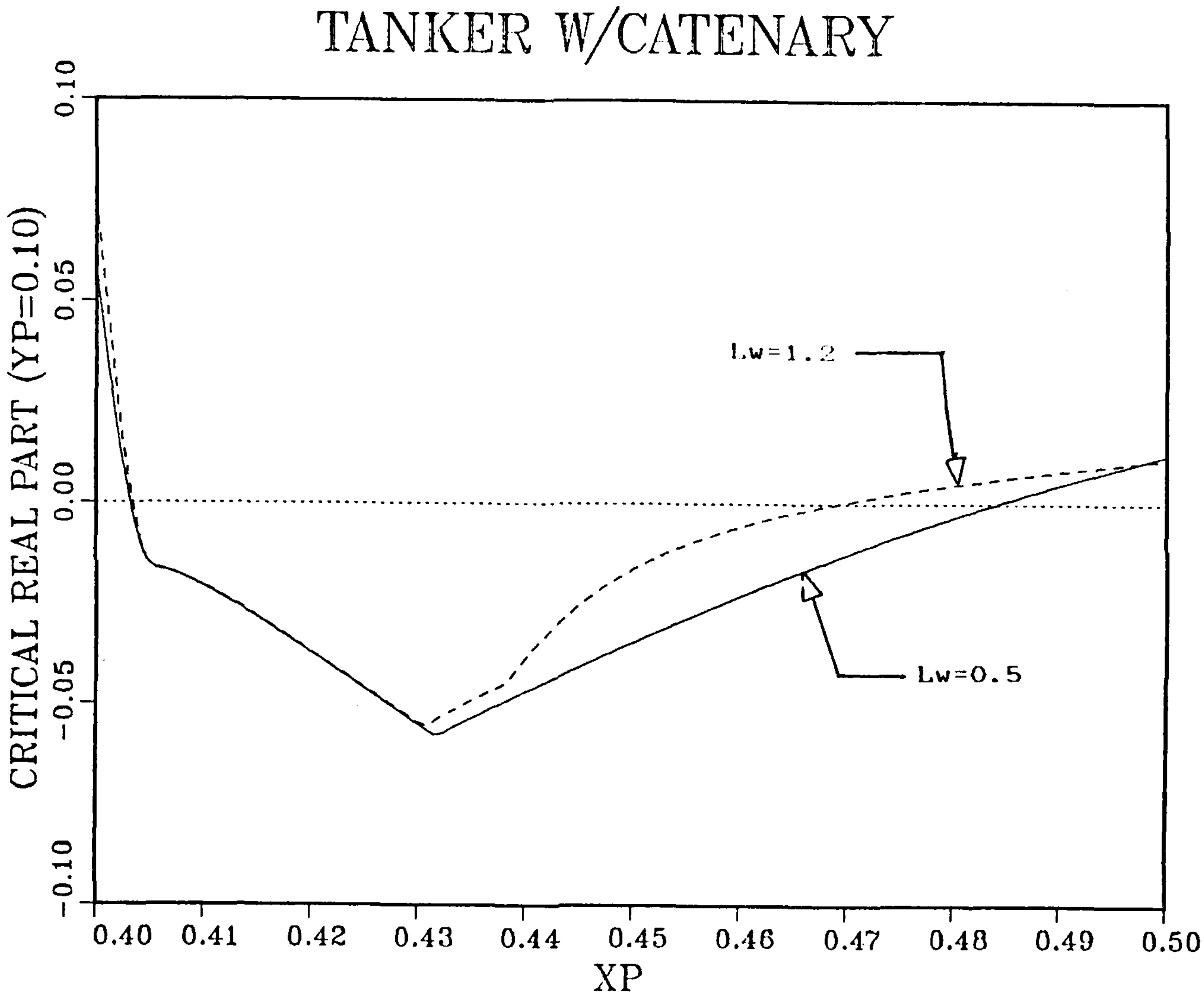


Figure 6. Critical Real Part vs. xp - Tanker

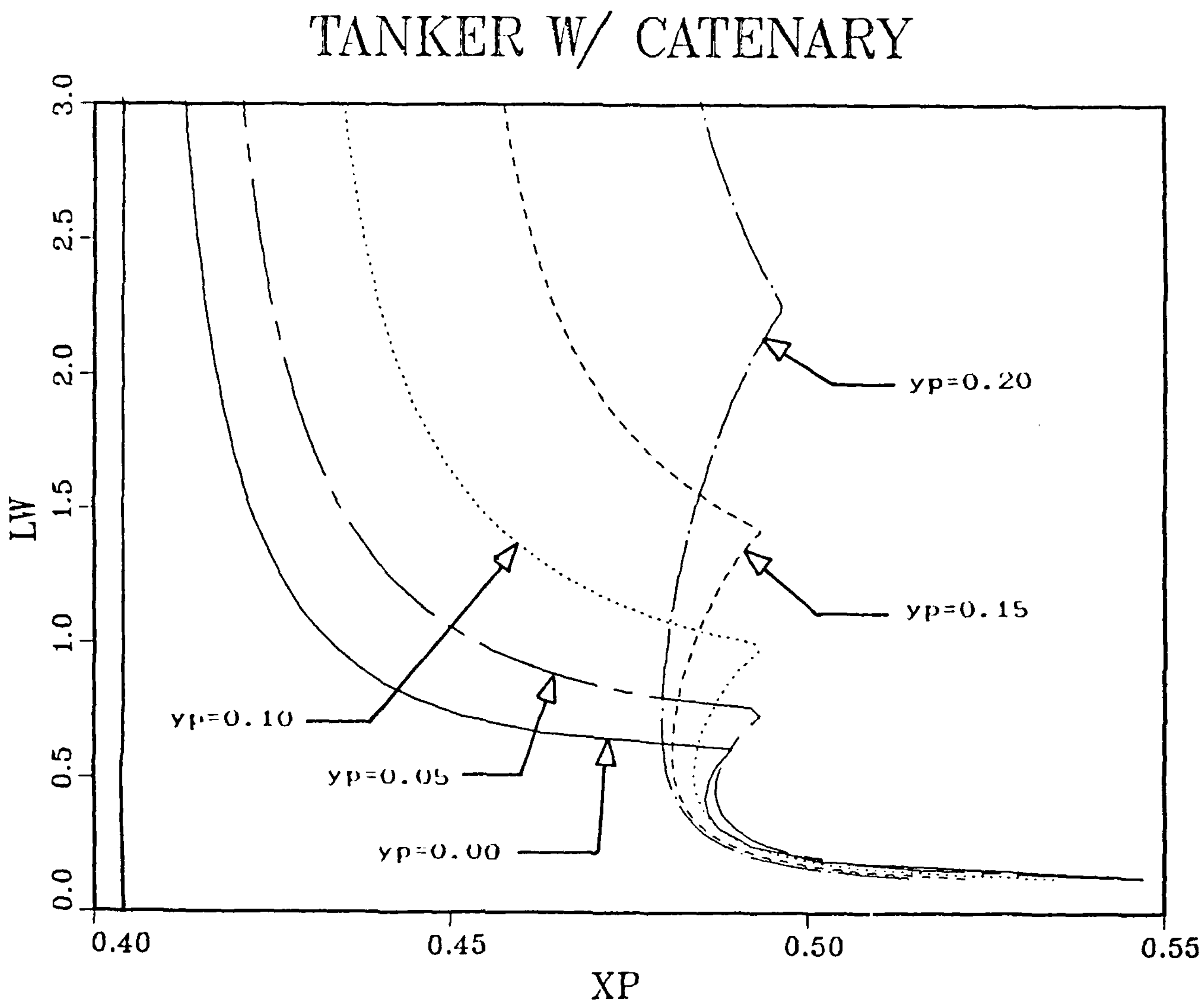


Figure 7. Lw vs. xp, yp>0 as parameter

xp=0.404 is a common crossing point for all curves. Each curve is formed by two cusps, with the upper cusp dominating with decreasing yp. Each cusp is the plot of different critical pair of eigenvalues; the "nose" in the curves is the point where they intersect.

Note how the stable region gets smaller with decreasing yp for Lw less than 0.7, for example, with yp=0.0 and Lw greater than 1.0, there is a very narrow range of xp where stability can be assured.

3. Figure 8: Critical Real Part vs. xp

TOWBIF1 was again used to form Figure 8, this time with one value for Lw (Lw=0.6) and three negative values for yp. The negative yp curves pass from stable to unstable regions, with the stable ranges for xp getting smaller as xp becomes more negative.

As in Figure 6, the curves are composites of those results curves which are critical over a particular range of xp.

4. Figure 9: Lw vs. xp, Negative Values of yp as Parameters.

Figure 9 data was generated from TOWBIF3, with yp=0.0 curve included to provide continuity with Figure 7.

The stable region gets smaller as yp decreases from 0.0. At yp=-0.10 the "nose" between upper and lower cusps appears to be tipping up, with the region inside the "nose"

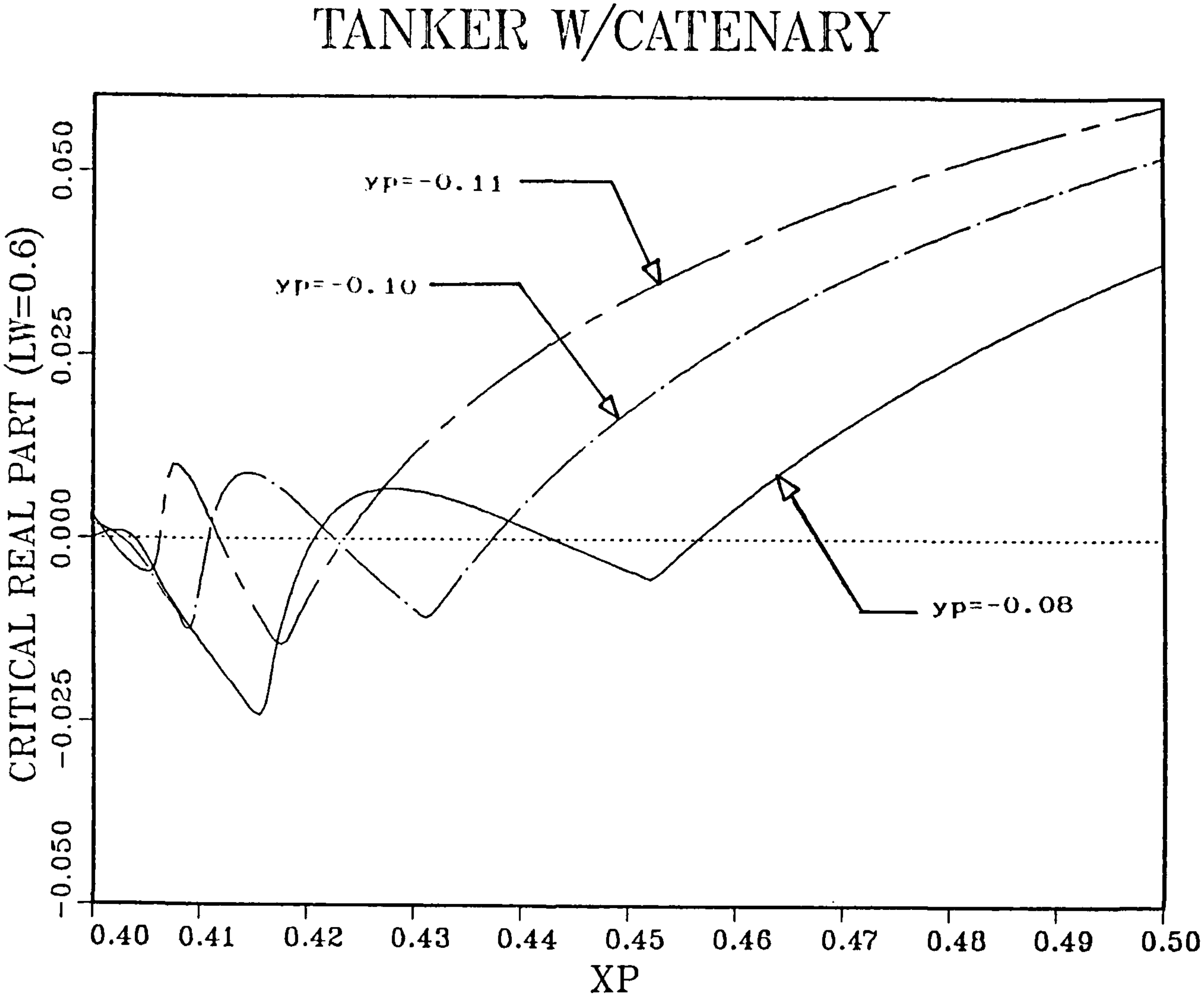


Figure 8. Critical Real Part vs. xp - yp<0

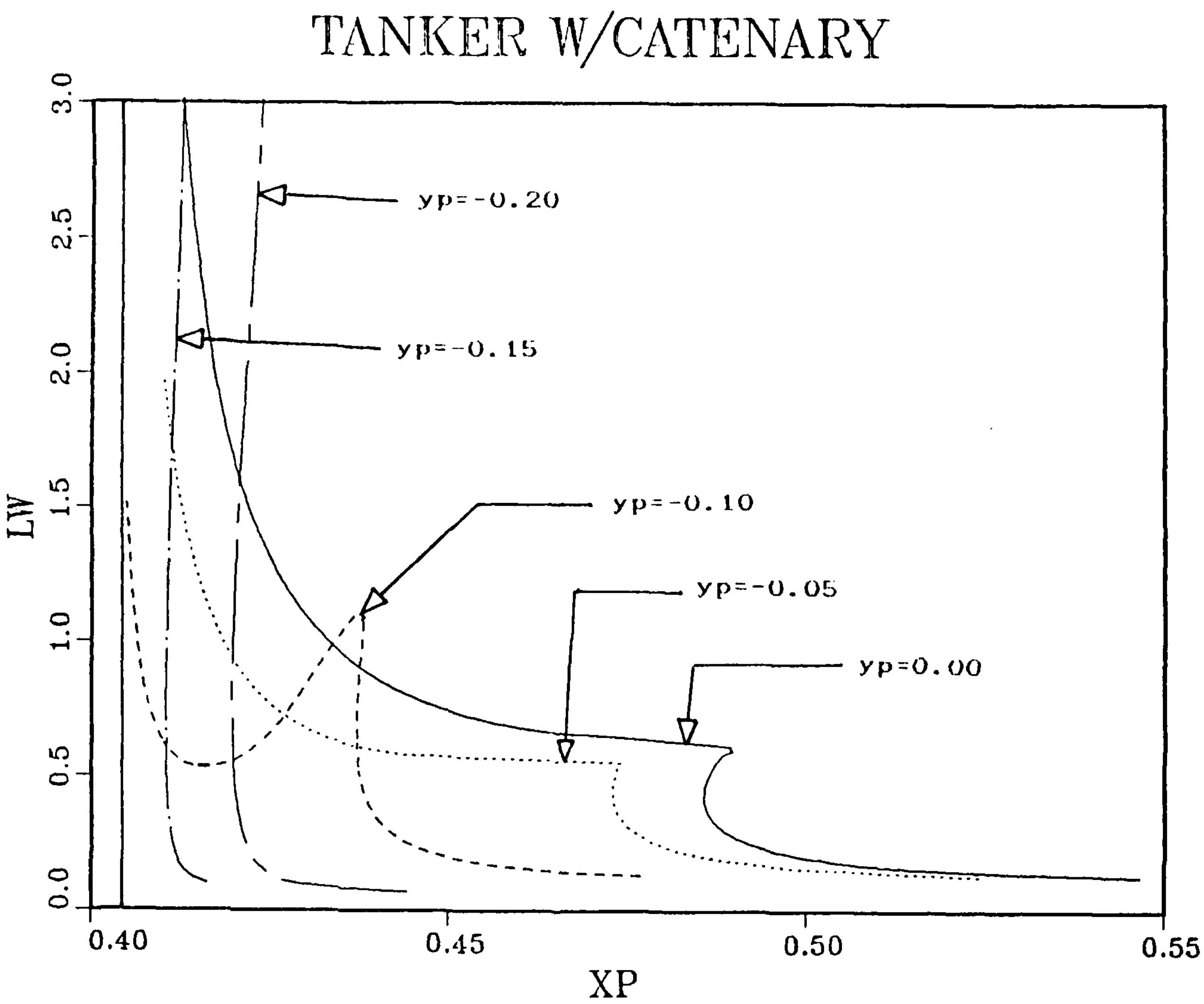


Figure 9. Lw vs. xp, yp<0 as parameter

being stable. The curves plotted in Figure 8 were formed using a value of Lw which cut through this nose, thus forming the sinuous curves which pass in and out of the stable region. Note that for the most negative values of yp, the cusps have disappeared, and the stable range of xp is slightly increasing.

5. Figure 10: Lw vs xp, Negative Values of yp as Parameters.

Figure 10 is a "close-up" of Figure 9, focusing on what is happening around yp=-0.10. The lower cusp tips up and merges with the upper to form a single curve. Note how the stable range of xp virtually disappears for Lw greater than 0.5 for yp=-0.10 and -0.11. As was seen in Figure 9, stable range for xp for Lw greater than 0.5 reappears with yp less than -0.15.

C. BARGE WITHOUT SKEG

The third vessel was a self-propelled version of the barge studied in Section A (not under power during tow), but without the skeg. As with the tanker, the presence of the propellor, simulated by a bias in the data file, introduces port-starboard asymmetry.

1. Figure 11: Critical Real Part vs xp for Lw=1.5

Figure 11 shows curves for three values of yp (greater than zero, zero, and less than zero) and one value of Lw. The curves show the stable range of xp to be between

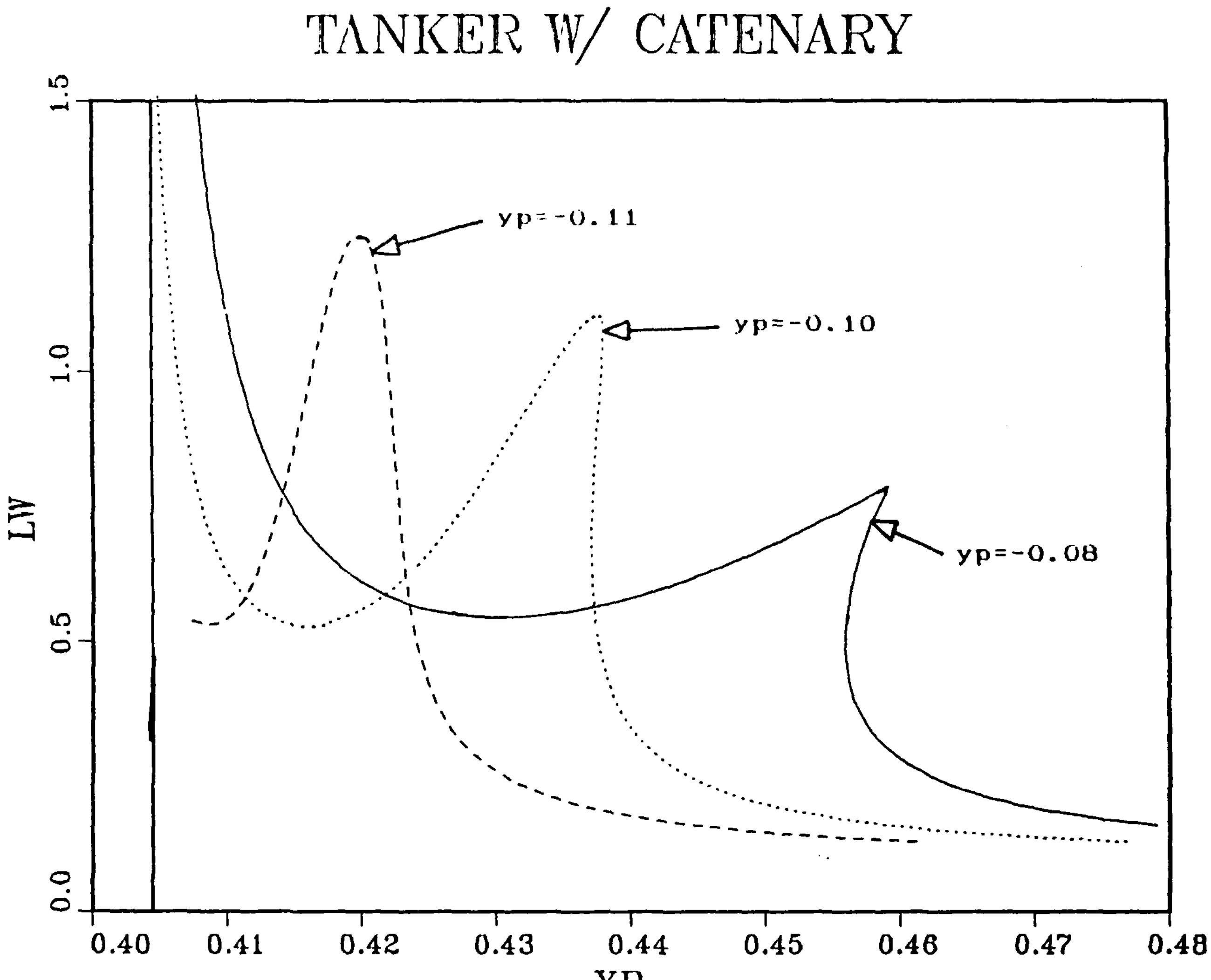


Figure 10. Lw vs. xp, yp<0, Close-up

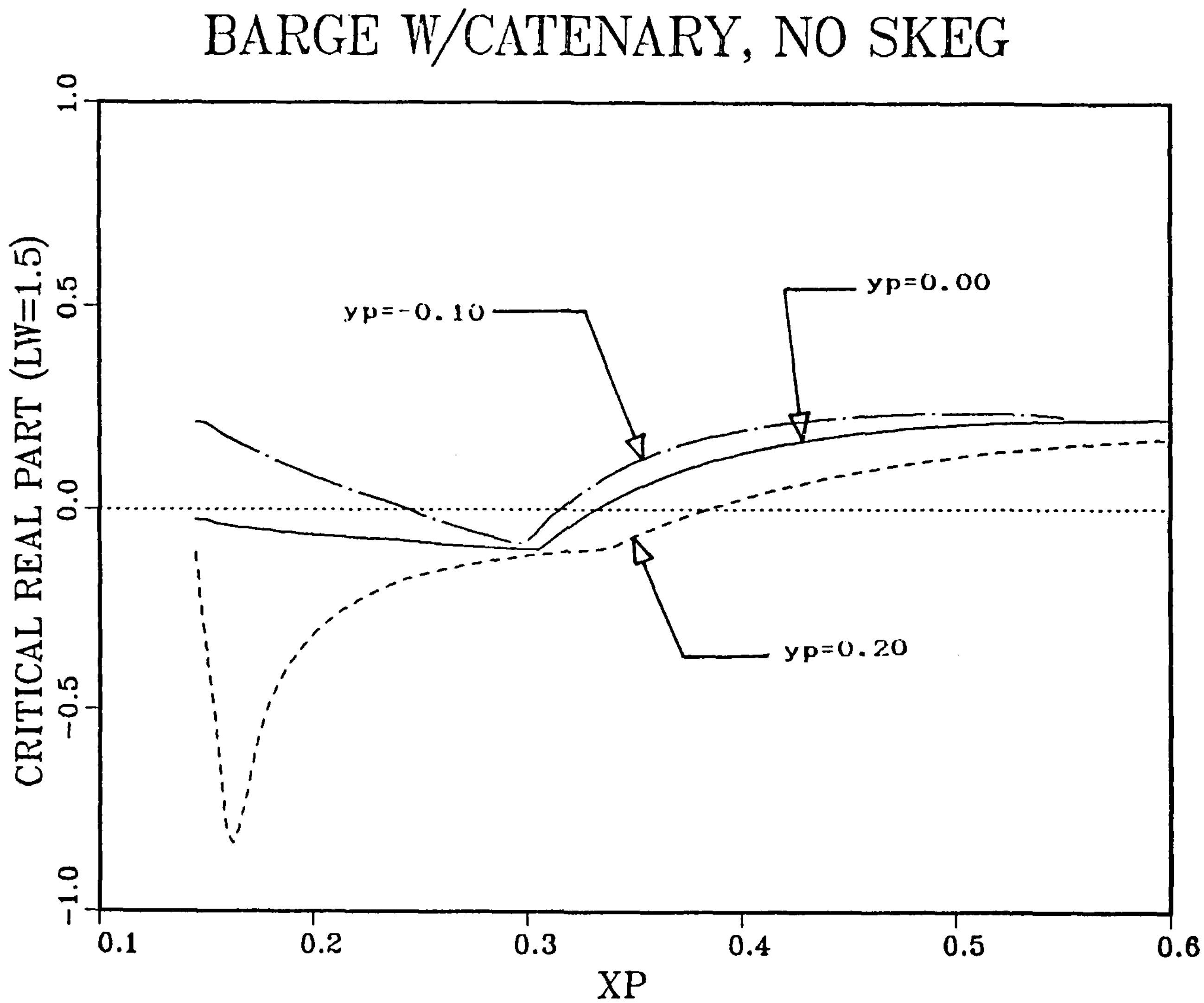


Figure 11. Critical Real Part vs. xp - Barge w/o skeg

the zero crossing points of the critical real parts, as in the tanker case. Also similarly to the tanker, the stable region increases with increasing yp. These results are opposite to the propellor-less barge with the skeg.

2. Figure 12: Lw vs xp

Figure 12 dramatically shows how decreasing yp reduces the stable region. The vertical line at xp=0.14 was common to all values of yp greater than and equal to zero. For values of yp less than zero, the smooth shape of the curve is apparent.

The tanker and self-propelled barge cases dramatically demonstrate the effect that a bias, like a propellor, can introduce to the stability of the system.

D. PRACTICAL OBSERVATIONS

Analysis of the graphs suggests some general principles which may be applied when conducting slow speed towing operations with the vessels discussed in this chapter. While these principles are of course not generally applicable to all vessels, they illustrate how the analysis techniques employed in this work can be applied to other vessels.

For the unpowered, symmetric barge with a skeg, the operator should have the towline attachment point as far out to either side as possible and the towline as long as

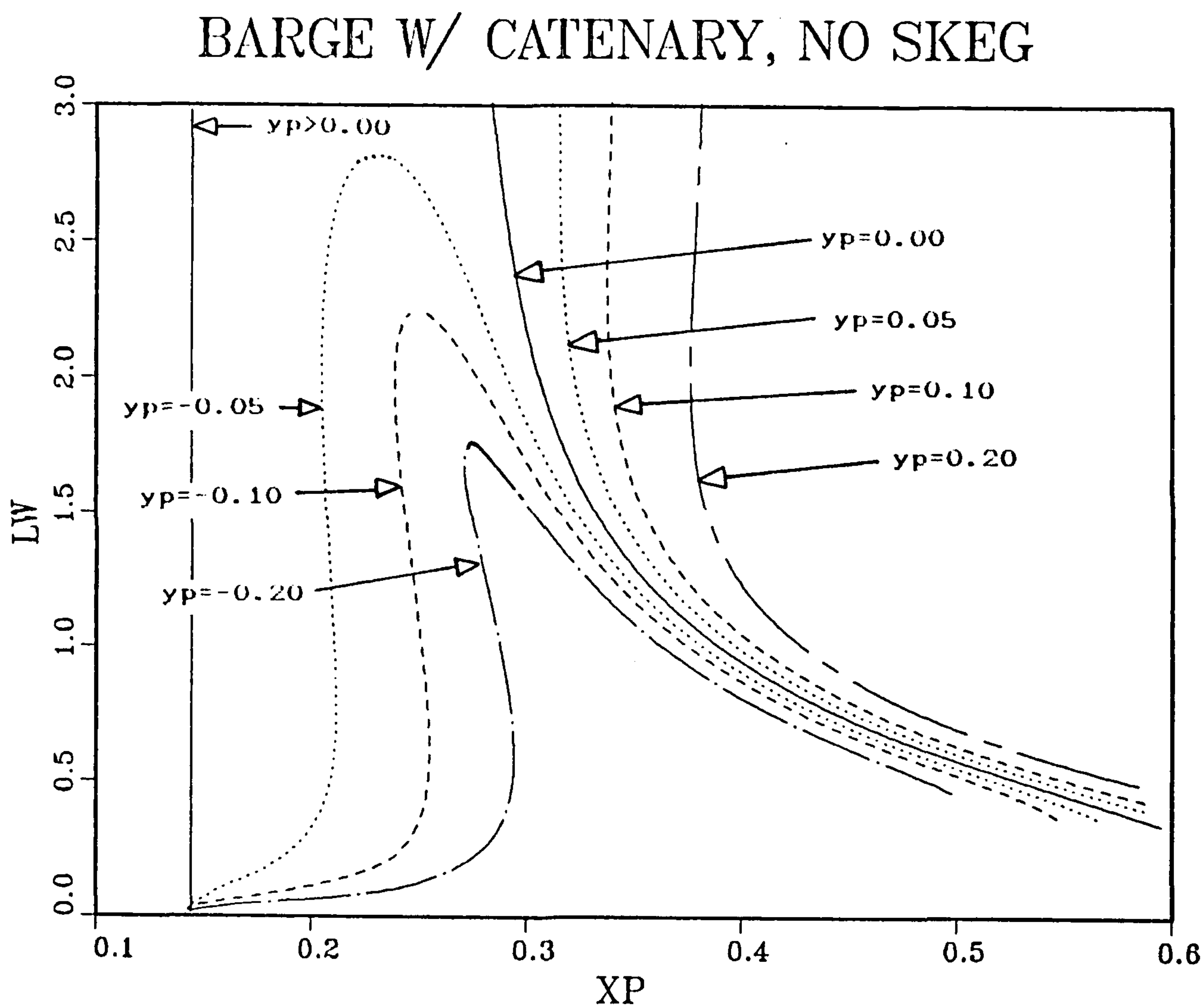


Figure 12. Lw vs. xp, yp as parameter

practical. The attachment point can then be placed at any location forward of the center of gravity with stability assured. Conversely, if the attachment point must be on the centerline, placing it as far forward as possible (about half the barge's length forward of the center of gravity) will assure stability for all towline lengths.

For vessels with an asymmetrical bias (e.g., with a propellor), but without skegs, the attachment point needs to be as far to the biased side as possible (in the cases of the tanker and self-propelled barge, the +yp or port side) and placed forward of the center of gravity the distance indicated on the graph for all towline lengths. Placement of the attachment point on the opposite side (in the cases studied, the starboard side) will virtually assure the system to be unstable.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This study highlighted the effect of athwartship position of the towline attachment point. The common assumption among ship operators prior to this reseach held that placing the towline on the centerline on the foremost point of the towed vessel would create the most advantageous towing situation. Studies such as [Ref. 2] have shown that towing stability can be dependent on the longitudinal placement of the attachment point. This research has shown that for certain conditions, attaching the towline off the centerline can also improve towed stability. The optimum towing configuration requires a combination of all three parameters - longitudinal and athwartship placement of the towline attachment point, and towline length.

The bifurcation technique used in this study can be used to produce stability information useful to ship designers and towing operators. Stability information can be assembled into a convenient graphical form that clearly defines the regions of stable and unstable operation based on the parameters the operator has the most control over - the placement and length of the towline.

For the ship designer, this technique can be useful in determining the implications particular design decisions would have on the vessel's performance under tow. Depending on the vessel's use, adjustments to the design can be made to improve towing stability, or the customer can be forewarned to avoid certain kinds of operations. Since nearly all vessels are towed at some time, towing performance should be analyzed for all vessels.

For the towing operator, this technique can provide readily available information about how a particular vessel will respond under tow. The operator can then adjust the towing parameters (i.e., placement the attachment point and/or length of the towline) so the tow will be in its most stable condition, or, if unavoidable, know that a particular towing situation will be potentially dangerous and make preparations to deal with it.

Since ship data is inputted through a data file, the towed performance of any vessel can be analyzed with this method, including structures such as offshore oil platforms. Existing vessels can be analyzed, as well as different loading conditions.

Two principal disadvantages are associated with this technique:

1. The programs are dependent on the quality of the data provided. Determining hydrodynamic coefficients and resistance data requires tow tank experiments and analysis, and are not obtained for most vessels;

2. The programs require large amounts of computer time and memory to run, which may not be available or too costly for potential users, especially to run extensive "what-if" scenarios. This problem may be alleviated as more inexpensive, high speed, high capacity micro- and personal computers become available.

B. RECOMMENDATIONS

This study was done for only one set of conditions. Further research can be done in determining the effect of varying conditions, such as different speeds or maneuvering by the towing vessel, on the stability of the tow. External forces are modelled by the bias in the data file. A systematized method of introducing biases into the data would enable the analysis of the effect of environmental conditions on the towing system.

Further work should be conducted to improve the "user-friendliness" of the programs. As currently configured, the programs must be run instructively, and graphics produced offline. This is a time consuming process which does not use the full capabilities of either the programs or the graphics capabilities of the mainframe. Program

improvements should focus on streamlining computations and user interaction, and incorporating graphics, with the goal of making it available as a ship design tool.

APPENDIX

Driver programs used in this thesis are shown here.
Subroutines can be obtained by contacting:

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Department of Mechanical Engineering
Naval Postgraduate School
Monterey, CA 93943

FILE: TOWBIF1 FORTRAN A1

```
      PROGRAM TOWBI1
C
C     BIFURCATION ANALYSIS OF TOWING SYSTEMS
C     PARAMETER DEPENDS ON IPAR
C       IPAR = 1 : XP
C              2 : YP
C              3 : LW
C     IT NEEDS SUBROUTINES FROM TOWING.FTN
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DOUBLE PRECISION MASSP,NVD,NV,NRD,IZZ,NR,LB,LEN,LW,
     1                 NO,NOU,NOUU,NVVV,NVRR,NVDD,NVU,NVUU,NRRR,NRVV,
     2                 NRDD,NRU,NRUU,ND,NDDD,NDVV,NDRR,NDU,NDUU,NVRD
C
      DIMENSION IV1(6),A(6,6),VV(3),X(6),WR(6),WI(6),Z(6,6),SV2(6)
C
      COMMON/INTGR/ISKEG,NREDP,ITYS,ID,IFDS,ISTAB,IPROP
      COMMON/SPAR/MASSP,LW,XPP,YPP,LB
      COMMON/SURGE/SU(7)
      COMMON/XSURG/XU,XUU,XUUU
      COMMON/SWAY/SW(15)
      COMMON/YAW/YA(16)
      COMMON/MTER/VCAR,RHO,ABS,CON1,CON2
      COMMON/RESIST/VEL(40),RESI(40)
      COMMON/VELE/UEL(100)
      COMMON/POSTN/XI,YI,ZI
      COMMON/GEOM/AL,RW,G,AET,HW,HW1
      COMMON/PROP/ALE,P,EY,DIA,ANIU
      COMMON/CTNR/XC(99),YC(99),ZC(99),TC(99)
      COMMON/INT1/IC
      COMMON/DOC/UC,ALPHA
      COMMON/UEPT/RLX,RLY,RLZ
      COMMON/SLOPE/PDRXX,PDRXY,PDRYX,PDRYY
      COMMON/SLAN/RXX6,RYY6,RXX,RYY
C
      OPEN (UNIT=35,FILE='BARGE2' ,STATUS='OLD')
      OPEN (UNIT=1,FILE='RES0',STATUS='NEW')
C
      OPEN (UNIT=11,FILE='RES1R',STATUS='NEW')
      OPEN (UNIT=12,FILE='RES2R',STATUS='NEW')
      OPEN (UNIT=13,FILE='RES3R',STATUS='NEW')
      OPEN (UNIT=14,FILE='RES4R',STATUS='NEW')
      OPEN (UNIT=15,FILE='RES5R',STATUS='NEW')
      OPEN (UNIT=16,FILE='RES6R',STATUS='NEW')
```

```
C
      OPEN (UNIT=21,FILE='RES1I',STATUS='NEW')
      OPEN (UNIT=22,FILE='RES2I',STATUS='NEW')
      OPEN (UNIT=23,FILE='RES3I',STATUS='NEW')
      OPEN (UNIT=24,FILE='RES4I',STATUS='NEW')
      OPEN (UNIT=25,FILE='RES5I',STATUS='NEW')
      OPEN (UNIT=26,FILE='RES6I',STATUS='NEW')
C
      CALL INPUTD(10)
      VCAR =VCAR*1.689D0
      MATZ =0
      IFLOW=1
C
      WRITE (*,1001)
      READ  (*,*)    IPAR
      WRITE (*,1002)
      READ  (*,*)    A1,A2
      WRITE (*,1003)
      READ  (*,*)    NUM1
      WRITE (*,1005)
      READ  (*,*)    IKB
      WRITE (*,1006)
      READ  (*,*)    NEQL
      IF (IKB.GT.NEQL) GO TO 500
      DO 1 I=1,NUM1
        WRITE (*,2001) I,NUM1
        AA=A1+(A2-A1)*(I-1)/(NUM1-1)
        IF (IPAR.EQ.1) XPP=AA
        IF (IPAR.EQ.2) YPP=AA
        IF (IPAR.EQ.3) LW =AA
        AL =LW*LB*0.3048D0
        ALE=AL
        CALL STABIL(IVV,VV,ISOL)
C
C       SET V=VV(K) FOR BIFURCATION ANALYSIS OF K-TH EQUILIBRIUM
C
        IF (IVV.NE.NEQL) GO TO 1
        V=VV(IKB)
        IF (DABS(V).GT.1.D0) STOP 1111
        CALL EQUILB(V,X,RES,RX,RY)
        CALL LINEAR(X,RES,A,RX,RY)
        CALL RG(6,6,A,WR,WI,MATZ,Z,IV1,SV2,IER1)
        IF (IER1.NE.0) STOP 2222
        CALL DEGSTB(DEGS,WR)
        WRITE (1,10) AA,DEGS
        DO 11 J=1,6
          JR=10+J
          WRITE (JR,10) AA,WR(J)
          JI=20+J
          WRITE (JI,10) AA,WI(J)
   11   CONTINUE
    1 CONTINUE
  500 STOP
   10 FORMAT (2D20.10)
 1001 FORMAT (' ENTER 1 : XP VARIATION',/,
     1        '       2 : YP VARIATION',/,
     2        '       3 : LW VARIATION')
 1002 FORMAT (' ENTER PARAMETER RANGE')
 1003 FORMAT (' ENTER NUMBER OF INCREMENTS')
 1005 FORMAT (' ENTER EQUILIBRIUM NUMBER')
 1006 FORMAT (' ENTER ESTIMATED NO. OF EQUILIBRIA')
 2001 FORMAT (2I5)
      END
```

FILE: TOWBIF2 FORTRAN A1

```
      PROGRAM TOWBI2
C     PROGRAM TOWBIF.FTN
C
C     BIFURCATION ANALYSIS OF TOWING SYSTEMS
C     PARAMETERS ARE: Xp, Yp
C     IT NEEDS SUBROUTINES FROM TOWING.FTN
C
C     USER DEPENDENT SUBROUTINES:
C       DEGSTB = CURVES ENCLOSING REGION II OF FIGURE 13
C                (SUBROUTINE DEGSTB IS IN TOWING.FTN)
C       DS1    = CURVES ENCLOSING REGION V OF FIGURE 13
C                (SUBROUTINE DS1 IS IN SPMBIF)
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DOUBLE PRECISION MASSP,NVD,NV,NRD,IZZ,NR,LB,LEN,LW,
     1                 NO,NOU,NOUU,NVVV,NVRR,NVDD,NVU,NVUU,NRRR,NRVV,
     2                 NRDD,NRU,NRUU,ND,NDDD,NDVV,NDRR,NDU,NDUU,NVRD
C
      DIMENSION IV1(6),A(6,6),VV(3),X(6),WR(6),WI(6),Z(6,6),SV2(6)
C
      COMMON/INTGR/ISKEG,NREDP,ITYS,ID,IFDS,ISTAB,IPROP
      COMMON/SPAR/MASSP,LW,XPP,YPP,LB
      COMMON/SURGE/SU(7)
      COMMON/XSURG/XU,XUU,XUUU
      COMMON/SWAY/SW(15)
      COMMON/YAW/YA(16)
      COMMON/MTER/VCAR,RHO,ABS,CON1,CON2
      COMMON/RESIST/VEL(40),RESI(40)
      COMMON/VELE/UEL(100)
      COMMON/POSTN/X1,Y1,Z1
      COMMON/GEOM/AL,RW,G,AET,HW,HW1
      COMMON/PROP/ALE,P,EY,DIA,ANIU
      COMMON/CTNR/XC(99),YC(99),ZC(99),TC(99)
      COMMON/INT1/IC
      COMMON/DCC/UC,ALPHA
      COMMON/UEPT/RLX,RLY,RLZ
      COMMON/SLOPE/PDRXX,PDRXY,PDRYX,PDRYY
      COMMON/SLAN/RXX6,RYY6,RXX,RYY
C
      OPEN (UNIT=35,FILE='BSKEG2',STATUS='OLD')
      OPEN (UNIT=11,FILE='RES1R',STATUS='NEW')
      OPEN (UNIT=12,FILE='RES2R',STATUS='NEW')
      OPEN (UNIT=13,FILE='RES3R',STATUS='NEW')
      OPEN (UNIT=14,FILE='RES4R',STATUS='NEW')
      OPEN (UNIT=15,FILE='RES5R',STATUS='NEW')
      OPEN (UNIT=16,FILE='RES6R',STATUS='NEW')
C
      CALL INPUTD(10)
      VCAR =VCAR*1.689D0
      AL   =LW*LB*0.3048D0
      ALE  =AL
      MATZ =0
      IFLOW=1
      EPS  =1.D-5
      ILMAX=1500
C
      WRITE (*,1001)
      READ  (*,*)    A1,A2
      WRITE (*,1002)
      READ  (*,*)    NUM1
      WRITE (*,1003)
      READ  (*,*)    B1,B2
      WRITE (*,1004)
      READ  (*,*)    NUM2
```

```
C
      WRITE (*,1005)
      READ  (*,*)     IKB
      WRITE (*,1006)
      READ  (*,*)     IDS
      DO 1 I=1,NUM1
        WRITE (*,2001) I,NUM1
        YPP=A1+(A2-A1)*(I-1)/(NUM1-1)

        XPP=B1
        CALL STABIL(IVV,VV,ISOL)
C
C       SET V=VV(K) FOR BIFURCATION ANALYSIS OF K-TH EQUILIBRIUM
C
        V=VV(IKB)
        IF (DABS(V).GT.1.D0) STOP 1111
        CALL EQUILB(V,X,RES,RX,RY)
        CALL LINEAR(X,RES,A,RX,RY)
        CALL RG(6,6,A,WR,WI,MATZ,Z,IV1,SV2,IER1)
        IF (IER1.NE.0) STOP 2222
        IF (IDS.EQ.1) CALL DEGSTB(DEOS,WR)
        IF (IDS.EQ.2) CALL DS1(DEOS,WR)
        DEOSOO=DEOS
        XPOO  =XPP
        L     =0
        DO 2 J=2,NUM2
C         WRITE (*,*) J
          XPP=B1+(B2-B1)*(J-1)/(NUM2-1)
          CALL STABIL(IVV,VV,ISOL)
C
C         SET V=VV(K) FOR BIFURCATION ANALYSIS OF K-TH EQUILIBRIUM
C
          V=VV(IKB)
          IF (DABS(V).GT.1.D0) STOP 1111
          CALL EQUILB(V,X,RES,RX,RY)
          CALL LINEAR(X,RES,A,RX,RY)
          CALL RG(6,6,A,WR,WI,MATZ,Z,IV1,SV2,IER1)
          IF (IER1.NE.0) STOP 2222
          IF (IDS.EQ.1) CALL DEGSTB(DEOS,WR)
          IF (IDS.EQ.2) CALL DS1(DEOS,WR)
          DEOSNN=DEOS
          XPNN=XPP
          PR=DEOSOO*DEOSNN
          IF (PR.GT.0.D0) GO TO 5
          L=L+1
          IF (L.GT.6) STOP 1000
          IL=0
          XPO=XPOO
          XPN=XPNN
          DEOSO=DEOSOO
          DEOSN=DEOSNN
    6     XPL=XPO
          XPR=XPN
          DEOSL=DEOSO
          DEOSR=DEOSN
          XPP=(XPL+XPR)/2.D0
          CALL STABIL(IVV,VV,ISOL)
          V=VV(IKB)
          IF (DABS(V).GT.1.D0) STOP 1111
          CALL EQUILB(V,X,RES,RX,RY)
          CALL LINEAR(X,RES,A,RX,RY)
          CALL RG(6,6,A,WR,WI,MATZ,Z,IV1,SV2,IER1)
          IF (IER1.NE.0) STOP 2222
          CALL DEGSTB(DEOS,WR)
          DEOSM=DEOS
```

```
      XPM=XPP
      PRL=DEOSL*DEOSM
      PRR=DEOSR*DEOSM
      IF (PRL.GT.0.D0) GO TO 5
      XPO=XPL
      XPN=XPM
      DEOSO=DEOSL
      DEOSN=DEOSM
      IL=IL+1
      IF (IL.GT.ILMAX) STOP 3100
      DIF=DABS(XPL-XPM)
      IF (DIF.GT.EPS) GO TO 6
      XP=XPM
      GO TO 4
    5 IF (PRR.GT.0.D0) STOP 3200
      XPO=XPM

      XPN=XPR
      DEOSO=DEOSM
      DEOSN=DEOSR
      IL=IL+1
      IF (IL.GT.ILMAX) STOP 3100
      DIF=DABS(XPM-XPR)
      IF (DIF.GT.EPS) GO TO 6
      XP=XPM
    4 LLL=10+L
      WRITE (LLL,10) XP,YPP
    3 XPOO=XPNN
      DEOSOO=DEOSNN
    2 CONTINUE
    1 CONTINUE
      STOP
   10 FORMAT (2D20.10)
 1001 FORMAT (' ENTER RANGE OF Yp VARIATION')
 1002 FORMAT (' ENTER NUMBER OF INCREMENTS IN Yp')
 1003 FORMAT (' ENTER RANGE OF Xp VARIATION')
 1004 FORMAT (' ENTER NUMBER OF INCREMENTS IN Xp')
 1005 FORMAT (' ENTER EQUILIBRIUM NUMBER')
 1006 FORMAT (' ENTER DEGREE OF STABILITY CONTROL')
 2001 FORMAT (2I5)
      END
C
      SUBROUTINE DS1(DEOS,WR)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION WR(6)
      DEOS1=-1.D30
      DO 1 I=1,6
        IF (WR(I).LT.DEOS1) GO TO 1
        DEOS1=WR(I)
        IJ=I
    1 CONTINUE
      DEOS2=-1.D30
      DO 2 I=1,6
        IF (IJ.EQ.I) GO TO 2
        IF (WR(I).LT.DEOS2) GO TO 2
        DEOS2=WR(I)
        IJJ=I
    2 CONTINUE
      DEOS=-1.D30
      DO 3 I=1,6
        IF (I.EQ.IJ.OR.I.EQ.IJJ) GO TO 3
        IF (WR(I).GE.DEOS) DEOS=WR(I)
    3 CONTINUE
      RETURN
      END
```

FILE: TOWBIF3 FORTRAN A1

```
C     PROGRAM TOWBIF3.FTN
C
C     BIFURCATION ANALYSIS OF TOWING SYSTEMS
C     PARAMETERS ARE: Xp, Lw
C     IT NEEDS SUBROUTINES FROM TOWING.FTN
C
C     USER DEPENDENT SUBROUTINES:
C       DEGSTB = CURVES ENCLOSING REGION II OF FIGURE 13
C                (SUBROUTINE DEGSTB IS IN TOWING.FTN)
C       DS1    = CURVES ENCLOSING REGION V OF FIGURE 13
C                (SUBROUTINE DS1 IS IN SPMBIF)
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DOUBLE PRECISION MASSP,NVD,NV,NRD,IZZ,NR,LB,LEN,LW,
     1                 NO,NOU,NOUU,NVVV,NVRR,NVDD,NVU,NVUU,NRRR,NRVV,
     2                 NRDD,NRU,NRUU,ND,NDDD,NDVV,NDRR,NDU,NDUU,NVRD
C
      DIMENSION IV1(6),A(6,6),VV(3),X(6),WR(6),WI(6),Z(6,6),SV2(6)
C
      COMMON/INTGR/ISKEG,NREDP,ITYS,ID,IFDS,ISTAB,IPROP
      COMMON/SPAR/MASSP,LW,XPP,YPP,LB
      COMMON/SURGE/SU(7)
      COMMON/XSURG/XU,XUU,XUUU
      COMMON/SWAY/SW(15)
      COMMON/YAW/YA(16)
      COMMON/MTER/VCAR,RHO,ABS,CON1,CON2
      COMMON/RESIST/VEL(40),RESI(40)
      COMMON/VELE/UEL(100)
      COMMON/POSTN/X1,Y1,Z1
      COMMON/GEOM/AL,RW,G,AET,HW,HW1
      COMMON/PROP/ALE,P,EY,DIA,ANIU
      COMMON/CTNR/XC(99),YC(99),ZC(99),TC(99)
      COMMON/INT1/IC
      COMMON/DOC/UC,ALPHA
      COMMON/UEPT/RLX,RLY,RLZ
      COMMON/SLOPE/PDRXX,PDRXY,PDRYX,PDRYY
      COMMON/SLAN/RXX6,RYY6,RXX,RYY
C
      OPEN (UNIT=35,FILE='TANKER2',STATUS='OLD')
      OPEN (UNIT=1,FILE='RES1R',STATUS='NEW')
      OPEN (UNIT=2,FILE='RES2R',STATUS='NEW')
      OPEN (UNIT=3,FILE='RES3R',STATUS='NEW')
      OPEN (UNIT=4,FILE='RES4R',STATUS='NEW')
C
      CALL INPUTD(10)
      VCAR =VCAR*1.689D0
      AL   =LW*LB*0.3048D0
      ALE  =AL
      MATZ =0
      IFLOW=1
      ILMAX=1500
      EPS  =1.D-5
C
      WRITE (*,1001)
      READ  (*,*)   A1,A2
      WRITE (*,1002)
      READ  (*,*)   NUM1
      WRITE (*,1003)
      READ  (*,*)   B1,B2
      WRITE (*,1004)
      READ  (*,*)   NUM2
C
      WRITE (*,1005)
      READ  (*,*)   IKB
```

```
      WRITE (*,1006)
      READ  (*,*)     IDS
      DO 1 I=1,NUM1
        WRITE (*,2001) I,NUM1
        LW =A1+(A2-A1)*(I-1)/(NUM1-1)
        AL =LW*LB*0.3048D0
        ALE=AL
        XPP=B1

        CALL STABIL(IVV,VV,ISOL)
C
C       SET V=VV(K) FOR BIFURCATION ANALYSIS OF K-TH EQUILIBRIUM
C
        V=VV(IKB)
        IF (DABS(V).GT.1.D0) STOP 1111
        CALL EQUILB(V,X,RES,RX,RY)
        CALL LINEAR(X,RES,A,RX,RY)
        CALL RG(6,6,A,WR,WI,MATZ,Z,IV1,SV2,IER1)
        IF (IER1.NE.0) STOP 2222
        IF (IDS.EQ.1) CALL DEGSTB(DEOS,WR)
        IF (IDS.EQ.2) CALL DS1(DEOS,WR)
        DEOSOO=DEOS
        XPOO  =XPP
        L     =0
        DO 2 J=2,NUM2
          XPP=B1+(B2-B1)*(J-1)/(NUM2-1)
          CALL STABIL(IVV,VV,ISOL)
C
C         SET V=VV(K) FOR BIFURCATION ANALYSIS OF K-TH EQUILIBRIUM
C
          V=VV(IKB)
          IF (DABS(V).GT.1.D0) STOP 1111
          CALL EQUILB(V,X,RES,RX,RY)
          CALL LINEAR(X,RES,A,RX,RY)
          CALL RG(6,6,A,WR,WI,MATZ,Z,IV1,SV2,IER1)
          IF (IER1.NE.0) STOP 2222
          IF (IDS.EQ.1) CALL DEGSTB(DEOS,WR)
          IF (IDS.EQ.2) CALL DS1(DEOS,WR)
          DEOSNN=DEOS
          XPNN=XPP
          PR=DEOSOO*DEOSNN
          IF (PR.GT.0.D0) GO TO 3
          L=L+1
          IF (L.GT.4) STOP 1000
          IL=0
          XPO=XPOO
          XPN=XPNN
          DEOSO=DEOSOO
          DEOSN=DEOSNN
    6     XPL=XPO
          XPR=XPN
          DEOSL=DEOSO
          DEOSR=DEOSN
          XPP=(XPL+XPR)/2.D0
          CALL STABIL(IVV,VV,ISOL)
          V=VV(IKB)
          IF (DABS(V).GT.1.D0) STOP 1111
          CALL EQUILB(V,X,RES,RX,RY)
          CALL LINEAR(X,RES,A,RX,RY)
          CALL RG(6,6,A,WR,WI,MATZ,Z,IV1,SV2,IER1)
          IF (IER1.NE.0) STOP 2222
          CALL DEGSTB(DEOS,WR)
          DEOSM=DEOS
          XPM=XPP
```

```
          PRL=DEOSL*DEOSM
          PRR=DEOSR*DEOSM
          IF (PRL.GT.0.D0) GO TO 5
          XPO=XPL
          XPN=XPM
          DEOSO=DEOSL
          DEOSN=DEOSM
          IL=IL+1
          IF (IL.GT.ILMAX) STOP 3100
          DIF=DABS(XPL-XPM)
          IF (DIF.GT.EPS) GO TO 6
          XP=XPM
          GO TO 4
    5     IF (PRR.GT.0.D0) STOP 3200
          XPO=XPM
          XPN=XPR
          DEOSO=DEOSM

          DEOSN=DEOSR
          IL=IL+1
          IF (IL.GT.ILMAX) STOP 3100
          DIF=DABS(XPM-XPR)
          IF (DIF.GT.EPS) GO TO 6
          XP=XPM
    4     WRITE (L,10) XP,LW
    3     XPOO=XPNN
          DEOSOO=DEOSNN
    2   CONTINUE
    1 CONTINUE
      STOP
   10 FORMAT (2D20.10)
 1001 FORMAT (' ENTER RANGE OF Lw VARIATION')
 1002 FORMAT (' ENTER NUMBER OF INCREMENTS IN Lw')
 1003 FORMAT (' ENTER RANGE OF Xp VARIATION')
 1004 FORMAT (' ENTER NUMBER OF INCREMENTS IN Xp')
 1005 FORMAT (' ENTER EQUILIBRIUM NUMBER')
 1006 FORMAT (' ENTER DEGREE OF STABILITY CONTROL')
 2001 FORMAT (2I5)
      END
C
      SUBROUTINE DS1(DEOS,WR)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION WR(6)
      DEOS1=-1.D30
      DO 1 I=1,6
        IF (WR(I).LT.DEOS1) GO TO 1
        DEOS1=WR(I)
        IJ=I
    1 CONTINUE
      DEOS2=-1.D30
      DO 2 I=1,6
        IF (IJ.EQ.I) GO TO 2
        IF (WR(I).LT.DEOS2) GO TO 2
        DEOS2=WR(I)
        IJJ=I
    2 CONTINUE
      DEOS=-1.D30
      DO 3 I=1,6
        IF (I.EQ.IJ.OR.I.EQ.IJJ) GO TO 3
        IF (WR(I).GE.DEOS) DEOS=WR(I)
    3 CONTINUE
      RETURN
      END
```

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